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A review of studies on forced, natural and mixed heat transfer to fluid and nanofluid flow in an annular passage

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ABSTRACT

The enhancement of the thermal performance of heat exchanging equipment transport energy at low financial cost by various techniques is presented in this review. Various annular passage configurations have been used in the reviewed studies, namely circular, ellipse, rectangular, square, triangular, and rhombic annular channels with different fluid and boundary conditions. The effect of eccentricity in both horizontal and vertical directions on heat transfer rate in most numerical and experimental investigations for horizontal and vertical annular passages is studied. The effects of heater length, as well as the Darcy, Prandtl, Reynolds, Grashof and Rayleigh numbers on heat transfer in concentric and eccentric annular passages are also investigated. In case of rotating the inner, outer or both cylinders of the annular cylinder arrangement, the generated secondary flow influences the heat transfer to fluid flow in an annular passage. The effect of nanofluid on the increased enhancement of heat transfer in an annular channel is presented. Related studies on curved, covered annular channels showed augmented heat transfer rate in comparison with straight annular channels. In this review, a good agreement is evident between experimental and numerical data, which could help researchers design thermal systems supported by annular passages with the goal of retarding energy consumption by equipment and machineries in applications that could ultimately contribute to appeasing the global energy crisis.

Contents

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1. Introduction

Environmental and economic sustainability have drawn the attention of researchers and prompted them to seek alternative methods that offer maximum energy at low cost. Thermal system channel configuration and heat transfer fluid type are significant to providing the greatest required energy transport.

Investigating forced, natural and mixed heat transfer to fluid flow in an annular passage is among the most important heat transfer studies, owing to its presence in several applications from heat exchangers, to reactors, packed beds, gas turbines, chemical industries, etc. There are numerous published investigations that were initiated decades ago, comprising experimental and numerical explorations that deal with different types of fluid and boundary conditions.

Rohsenow et al. [1] distinguished four fundamental thermal boundary conditions with the potential to be applied in annular passages, as follows:

First kind: Uniform temperature at one wall (different from the incoming fluid temperature), while the other wall is at uniform entering fluid temperature.
Second kind: Uniform heat flux at one wall (i.e., adiabatic with zero heat flux) and the other wall is insulated.
Third kind: Uniform temperature at one wall (unlike the entering fluid temperature) and the other wall is insulated.
Fourth kind: Uniform heat flux at one wall, and the other wall maintains entering fluid temperature.

There are also other types of boundary conditions represented by varying and non-zero uniform heat flux at both walls of an annular passage.

In the last decade, the demand for energy has increased due to global development. Techniques used for saving energy and cost are provided by changing the flow channel configurations besides introducing high thermal conductivity fluid, such as nanofluid, which enhances thermal performance.

Throughout the present review, the subject matters of interest are investigated systematically, such as temperature distribution, thermal stresses, thermal length, heat transfer coefficient, pressure drop, and velocity profile. Some studies have also addressed the effect of a rotating inner and/or outer pipe and the effect of eccentricity on heat transfer processes in an annular passage.

The geometry of annular passages in engineering applications is available in various configurations, including circular, rectangular, elliptical, conical, polygonal, rhombic, triangular, square, and non-uniform, as found in concentric and eccentric configurations. A number of researchers have employed a concentric annular passage, meaning that the center line of the inner pipe has the same coordinates as that of the outer pipe, while others have used an eccentric annular passage whereby the inner pipe's center line does not have the same coordinates as that of the outer pipe. More recently investigations have been conducted on the accuracy of the heat transfer process in annular passages, and a good agreement is identified relative to other studies, as referred to in the present paper.

The purpose of this review paper is to clarify the economic value of achieving highly efficient energy transport at reduced cost via different approaches, including change in the structural configuration of thermal systems and employing high thermal conductivity fluids.

Due to an affluent number of available investigations on concentric and eccentric annular passages, this review is subdivided into two groups.

2. Heat transfer and fluid flow in concentric annular passage

Earlier studies with focus on forced, natural and mixed heat transfer to fluid flow in an annular passage were pioneered by Taylor [2], Dufinescz and Marcus [3], Zerban [4], Foust and Christian [5], Jakob and Rees [6], TEMA [7], Monrad and Pelton [8], Davis [9], Lorenzo and Anderson [10], Chen et al. [11], McMillan and Larson [12], Carpenter et al. [13], Bailey [14], Migushiva [15], Trefethen [16], MacLeod [17], Barrow [18], and Murakawa [19,20].

They have adopted numerical and experimental forms of investigating forced, natural and mixed heat transfer to fluid flow with vertical or horizontal annular passages and rotating or non-rotating flow for varying boundary condition, e.g., uniform heat flux or a wall with uniform temperature either for the inner pipe, outer pipe or both. The researchers have also applied various types of fluid in their studies. Diverse results were obtained, including on the effect of step ratio between inner and outer pipe, eccentricity, surface roughness, type of fluid, and fluid velocity in an annular passage on the heat transfer processes, temperature profiles of fully developed flow, thermal stresses and thermal length. Prior studies have contributed better insight into current research works, some of which are mentioned in this review paper. Generally, the obtained results indicate enhanced heat transfer rate due to effective flow channel shape and fluid type, which yield greater energy harvest at lower expense.

2.1. Heat transfer and fluid flow in horizontal concentric annular passage

Experimental and numerical studies have been carried out that investigate two-dimensional natural and mixed convection heat transfer in horizontal, concentric annular channels for circular cylinders. The effect outcomes of cylinder curvature, Prandtl number, Rayleigh number and ratio of the radius between inner and outer cylinders on heat transfer have been reported by Grigull and Hauf [21], Mack and Bishop [22], Powe et al. [23,24], Kuehn and Goldstein [25], Caltagirone [26], Custer and Shaughnessy [27], Burns and Tien [28], Kuehn and Goldstein [29], Vasseur et al. [30], Date [31], Glakpe et al. [32], Kolesnikov and Bubnovich [33], Kumar [34], Himasekhar and Bau [35], Yoo et al. [36], Mota and Saatdjian [37,38], Yoo [39], Labonia and Gui [40], Charrier-Mojatabi and Mojtabi [41],

Nomenclature

Ar	aspect ratio
b	mass average value
Bu	buoyancy parameter, $\overline{Gr_b}/Re_b^{2.7}$
a_1	inner radius of annulus (m)
a_2	outer radius of annulus (m)
$D1$	diameter of inner cylinder (cm)
$D2$	diameter of outer cylinder (cm)
f	normalized Nusselt number, $Nu_{\exp}/Nu_b$
Gr	Grashof number
$\overline{Nu}$	average Nusselt number
Nu_B	Nusselt number at bulk temperature
Pr_B	Prandtl number at bulk temperature
Re_B	Reynolds number at bulk temperature
Ra	Rayleigh number
rr	radius ratio, $=Ro/Ri$
Ta	Taylor number
T_E	temperature at entrance section (K)
T_w	temperature at wall (K)

Greek letters

ε	eccentricity (m)
Ω	oscillating frequency (cycles/s)
Γ	radii ratio
Θ	temperature dimensionless
Φ	tangential direction

Dyko et al. [42], Shu [43], Chung et al. [44], Yoo and Han [45], Mizushima et al. [46], Dyko and Vafai [47], Francis et al. [48], Leppinen [49], Yoo [50], and Petrone et al. [51]. In numerical studies, different models based on finite difference, along with element and volume method have been employed, demonstrating adequate agreement with experimental data. It was also observed that heat transfer augmentation occurred with the increase of Prandtl and Rayleigh numbers as well as aspect ratio and decreased annular passage inclination. In contrast, numerous experimental and numerical studies related to heat transfer in horizontal concentric non-circular annular that for ellipse have been conveyed by Schreiber and Singh [52], Elshamy et al. [53], Saatdjian et al. [54], Zhu et al. [55], Djezzar and Daguenet [56], Sakr Ramadan et al. [57], and Mahfouz and Badr [58], square investigated by Chang et al. [59], Yang and Farouk [60], Moukalled and Acharya [61], Asan [62], Shu and Zhu [63], Peng et al. [64], and Costa and Raimundo [65]; polygonal investigations were done by Ratkowsky and Epstein [66], and Wang [67]; conical assessments were performed by Wimmer [68], Balatka and Mochizuki [69], and Akira and Kaoru [70]; rhombic research was presented by Moukalled et al. [71] and Farinas et al. [72]; and triangular investigations were performed by Xu et al. [73], Xu et al. [74], and Yu et al. [75].

2.1.1. Stationary cylinder/experimental studies

Miller et al. [76] studied turbulent heat transfer to water flowing in an annulus with a heated inner pipe. The effect of space ratio, Reynolds number and heat flux on the enhancement of heat transfer was demonstrated. The obtained experimental results were 20% higher than the calculated values obtained using Colburn's equation for internal flow in pipes for an equivalent diameter. Bergles and Newell [77] presented an experimental study on the effect of increasing the intensity of ultrasonic vibration on heat transfer to water flowing in annuli. It was observed that at low flow velocities and high heat flux (non-boiling) the local heat transfer coefficient increased. Schmidt [78] reported a series of solutions in a study of heat transfer with fully developed laminar flow in the thermal entrance region of circular pipes and annular passages. He used different boundary conditions involved in changing the temperature or heat flux at the outer and inner wall. The calculated Nusselt number values were obtained based on solutions from the second and third types, in agreement with Lundberg et al [79], Sellars et al. [80] and Munakata [81]. Quarmby [82] carried out an empirical study on a thermal entrance with fully developed fluid flow in a horizontal, concentric, annular channel. Observations were made on the effect of radius ratio and Reynolds number on thermal entrance length. Quarmby and Anand [83,84] conducted research on turbulent heat transfer and fluid flow in a concentric annular passage with constant wall temperature and uniform heat flux. It was noted that the Nusselt number values for the boundary conditions of uniform heat flux are higher than those for constant wall temperature. Donne and Meerwald [85] studied the heat transfer and friction loss of turbulent air flow in smooth annuli at high temperature. The measured subsonic turbulent air flow in smooth annuli had diameter ratios of 1.99 and 1.38, with an inner pipe heated up to 1000 °C. The Nusselt numbers obtained were correlated with Eq. (1).

$$Nu_B = 0.018\left(\frac{D_2}{D_1}\right)^{0.16} Re_B^{0.8} Pr_B^{0.4}\left(\frac{T_W}{T_E}\right)^{-0.2} \tag{1}$$

It is observed that Petukhov and Roizen [86] associated well with Eq. (1) at low temperature differences ($T_W/T_E \to 1$).

Also, the average Nusselt numbers at the inner pipe of the annulus are given by the correlation in Eq. (2).

$$Nu_B = 0.0217\, Re_B^{0.8} Pr_B^{0.4}\left(\frac{T_W}{T_E}\right)^{-0.2} \tag{2}$$

Good accord was attained for circular tubes by Donne and Bowditch [87] in experimental investigations. Their data was presented as a correlating factor, $A=(Nu_B/Re_B{}^{0.8}Pr_B{}^{0.4})T_W/T_B=1$ with the diameter ratio ($D1/D2$) and compared with previous theories and empirical findings reported by Donne and Meerwald [88], Petukhov and Roizen [86], Wilson and Medwell [89], Kays and Leung [90] Deissler and Taylor [91], Sheriff and Gumley [92], Barthels [93], Rapier [94], Puchov and Vinogradov [95], and Buleev et al. [96,97], as shown in Fig. 1.

Heikal and Hatton [98] presented predictions and measurements of fully developed turbulent non-axisymmetric flow and heat transfer in an annular channel by implementing the turbulence model. They showed a good agreement with experimental data, especially for the velocity profile, friction factor and shear stress. Optimal agreement was additionally demonstrated between the predicted and measured data when the circumferential to radial mass diffusivity ratio of heat was maintained at 2 over the entire cross section. Robinson and Walker [99] obtained a value of circumferential heat diffusion in a symmetrical annular passage for turbulent flow and compared the results with theoretical solutions.

Togun et al. and Oon et al. [100,101] conducted an investigation on the turbulent heat transfer of fluid flow in a horizontal concentric annular pipe with steps. The focus was on the effect of step height, heat flux, and Reynolds number on heat transfer rate in

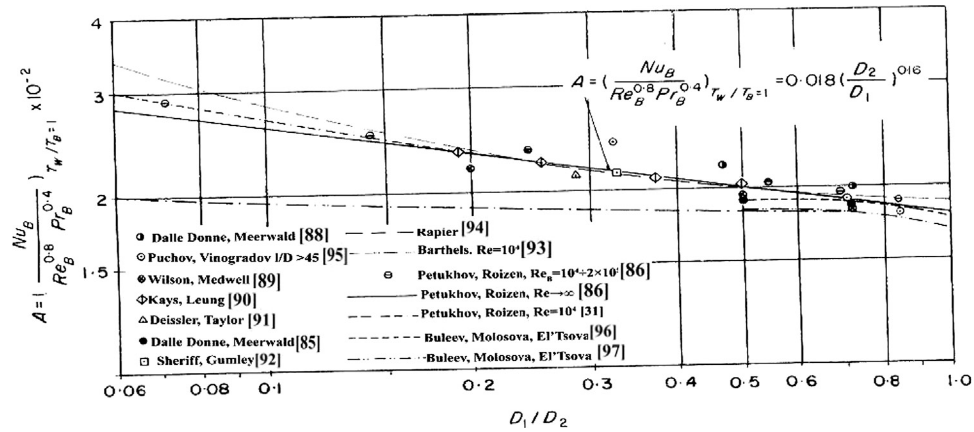


Fig. 1. Comparison factor $A=(Nu_B/Re_B^{0.8}Pr_B^{0.4})_{TW/TB=1}$ and ratio diameter (D_1/D_2).

an annular passage, where the maximum enhancement of heat transfer was roughly 18% compared to a straight pipe.

Core annular flow entails water-lubricated transport of heavy oil, whereby the technology of developing energy in this field is studied. Ghoh et al. [102] presented a fine review paper on previous studies that concentrated on hydrodynamics and the stability of oil–water core annular flow. Furthermore, Kaushik et al. [103] performed a study on oil and water flow through an annular passage with abrupt contraction and expansion using the VOF method. Profiles of velocity, pressure and volume fraction were created for oil and water flow in sudden contraction and expansion.

Nada [104] adopted the results of an experimental study on natural heat transfer to horizontal and inclined annular fluid layers. The observations indicated increased heat transfer rate with increased Rayleigh number and annular space and decreased annular passage inclination. Yang et al. [105] experimentally studied the natural convection heat transfer in a horizontal annulus with a square heating element at different positions in the inner cylinder. According to the outcome, the effect of heated element placement in the annular section on local heat transfer was shown as well as the maximum value when the heated element was placed at 90 degrees from the bottom.

2.1.2. Stationary cylinder/numerical studies

Stein and Begell [106] explored turbulent water flow and heat transfer in internally-heated annuli by implementing cosine and uniform length-wise heat flux distributions; 900 evaluates of local heat transfer coefficients of water flow with a heated inner pipe were computed. No considerable effect of cosine heat flux distribution was observed on the heat transfer coefficients. Chen and Yu [107] also studied turbulent heat transfer to flowing liquid metals in concentric annular channels. They focused on the influence of variable heat flux and entrance region dimensions on Nusselt number, and indicated that the predicted Nusselt number is in agreement with the experimental value. Lee et al. [108] presented numerical heat transfer results in fully developed flow by using a K–ε equation model in an annular pipe with rectangular roughness. A greater improvement in Nusselt number was attained by using a curvature correlation model as opposed to that with the standard K–ε equation model. They additionally achieved the highest Nusselt number value near the reattachment point of the separated flow which validated later by Hussein et al. [109–115] and Tuqa et al. [116]. The computational results showed good agreement with previous investigations reported by Kang [117], Kang and Choi [118], Lee [119], and Hong et al. [120]. Ho and Lin [121] numerically examined heat transfer to air–water flow in a horizontal concentric and eccentric cylindrical annulus with constant heat flux at the outer wall, and isothermal condition at the inner wall. A rise in heat exchange transfer to the air–water interface occurred in the mixed boundary condition. Ahn and Kim [122] accomplished analytical and experimental studies of heat transfer and fully developed fluid flow in rough annuli by using artificial roughness elements on the wall of the inner pipe, outer pipe or both. The heat transfer coefficient enhanced owing to the roughness element effect on turbulence.

Seo et al. [123] and Seo and Hyung [124] used direct numerical simulation (DNS) of turbulent heat transfer and flow structure in a horizontal concentric annular pipe. The turbulent thermal structures near the outer wall seemed to be more active than those near the inner wall due to the vortex regeneration processes between the inner and outer wall. Yu et al. [125] analyzed the computed characteristics of turbulent flow and convection in concentric annuli with a uniform heated inner pipe and unheated outer pipe. Their investigation was dependent on a previous model reported by Churchill and Chen [126] and MacLeod [17]. The results achieved from the numerically computed solutions for Nu number (Nu_0, Nu_1, Nu □) by using different Prandtl numbers demonstrated good agreement with prior experimental data on water reported by Dufinescz and Marcus [3], Zerban [4], T.E.M.A. [7], Monrad and Pelton [8], Mc Millan and Larson [12], Carpenter et al. [13], Trefethen [16], Miller et al. [76], Quarmby [82], Petukhov and Roizen [127], Roberts and Barrow [128], Leung [129], and Vilemas et al. [130] and predictions by Kays and Leung [90], as shown in Figs. 2–4. Meta and Orhan [131] performed a numerical study on thermally fully developed flows and hydro-dynamically-to-flow laminar forced convection heat transfer in a micro-channel between two concentric cylinders. They applied two types of thermal boundary conditions, the first case of which was uniform heat flux at the inner pipe and the other being uniform heat flux at the outer pipe. Increased Nusselt number was seen as Knudsen and Brinkman numbers decreased, and aspect ratio increased. Rouiss et al. [132] developed turbulence models by using direct numerical simulation (DNS) to study fluid flow and heat transfer in an annular pipe with random heat flux value at the outer and inner walls. Evidently, when heat flux increased from 1 to 100, the Nusselt number increased at the inner pipe and decreased at the outer pipe.

Several studies have dealt with immiscible liquids in horizontal concentric annular channels as represented by Ishii and Mishima [133] who showed the correlation of droplet entrainment in the equilibrium region of droplet liquid film by gas flow in an annular passage. The correlation was developed using experimental data and a simple model. The predicted data was in accord with experimental water data, which may encourage researchers to

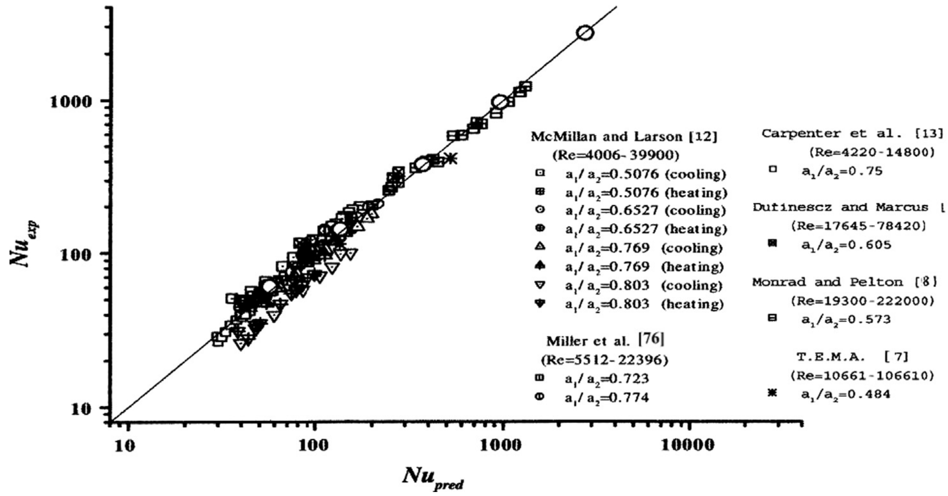


Fig. 2. Comparison of predicts values [125] with experimental data for water and predictions of Kays and Leung [90].

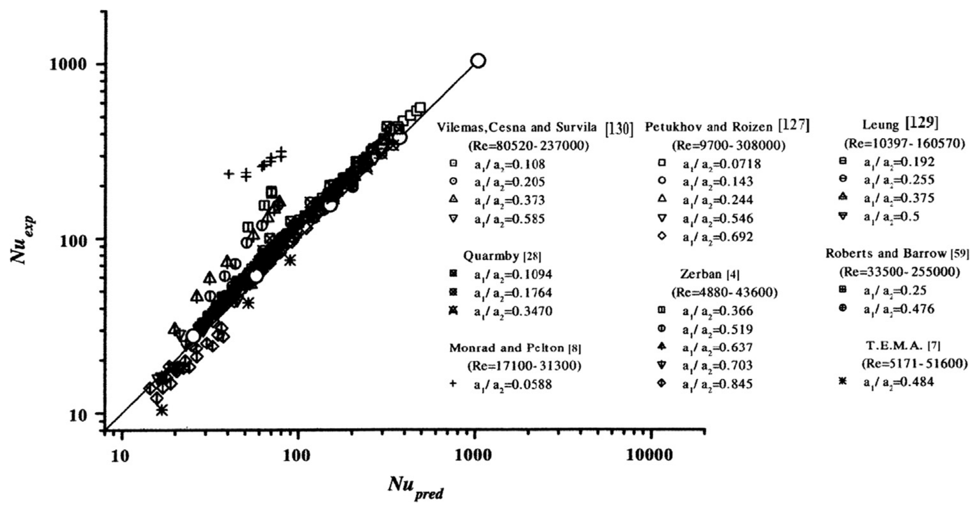


Fig. 3. Comparison of predicts values [125] with experimental data for air and predictions of Kays and Leung [90].

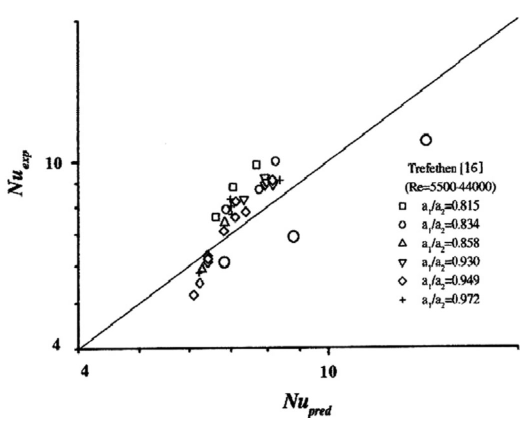


Fig. 4. Comparison of predicts values [125] with experimental data for mercury and predictions of Kays and Leung [90].

further develop on such studies. Shahidi and Ozbelge [134] investigated turbulent heat transfer of two immiscible liquids (water and oil) flowing in a horizontal concentric annular passage. They assessed the effect of liquid velocity, inlet temperature and aspect ratio on the heat transfer coefficient, and it was seen that with the increase of liquid velocity and inlet oil temperature as well as a decrease of aspect ratio, the volumetric heat transfer coefficient increases. Gordon and Norman [135] applied an energy equation to solve the fully-developed laminar flow of two immiscible liquids with uniform heat flux at the wall in a horizontal, concentric cylindrical passage. The heat transfer from the annular liquid to the core liquid augmented due to the core liquid's greater viscosity. Gelfgat et al. [136] numerically studied the improvement of a mass transfer product by interface separating the flow of two immiscible fluids in a horizontal annular cylindrical passage with heated inner or outer cylinder. The results indicate that a rise in mass transfer rate took place with a decrease in radius ratio and there was no effect of the heated annular cylinders observed on mass transfer rate. Marta et al. [137] theoretically investigated the natural heat transfer of nanofluid flow in a concentric cylindrical pipe with different uniform temperatures. An increase in heat transfer coefficient was noted with increasing nanoparticle friction volume and increasing nanofluid temperature. The results also revealed that higher heat transfer rate occurs with smaller nanoparticle size.

On the other hand, for three-dimensional mixed and natural convection heat transfer in horizontal concentric annular was studied by Tanaka et al. [138], Rao et al. [139], Fusegi and Farouk [140], Rao et al. [141], Vafai and Ettefagh [142], Yang and Farouk [143], Choi and Kim [144,145], Charrier-Mojtabi [146], Yeh [147], Petrone et al. [148], and Adachi and Imai [149]. In the investigations, more details and accurate data related to the local heat transfer coefficient were used. They also determined the total heat

transfer rate in an annular passage by applying Eq. (3) to calculate the mean Nusselt number in three-dimensional form and adequate agreement was achieved with previous results.

$$\overline{Nu}_{3D} = \frac{1}{\pi}\int_0^A \int_0^\pi Nu(\theta, Z)\, d\theta\, dz \tag{3}$$

Roschina et al. [150] focused on two-dimensional natural convection in horizontal, concentric, annular cylinders using a mathematical modeling approach and compared the influence of the maximum temperature in a horizontal annular cylinder with different geometries. Shi et al. [151] applied a finite difference method based on the lattice Boltzmann model to simulate the heat transfer of natural convection in a horizontal concentric annular passage. It was seen that the average Nusselt number values agree with values attained in previous numerical and experimental studies by Kuehn and Goldstein [152], and Shahraki [153] (Table 1).

Waheed [154] presented a numerical study of simulated natural heat transfer between two horizontal concentric annular passages. According to results, the heat transfer in the annular passage increased with decreased annular space width, also Prandtl and Rayleigh number, and different temperature ratios augmented the heat transfer rate. Sambamurthy et al. [155] numerically studied the two-dimensional natural convection of a horizontal annular cylinder with an inner heated solid square cylinder and outer isothermal circular cylinder. They also studied an annular cylinder with inner solid circular cylinder for comparison with an inner square cylinder. Generally, the numerical results revealed that the average Nusselt number depends on the average inner boundary temperature, and also, the results obtained are very useful in designing thermal systems. Furthermore, Yu et al. [156] used the finite volume method to study the natural convection heat transfer in a horizontal annular cylinder with an inner triangular cylinder and outer circular cylinder. The results signify that the Prandtl number's impact on local heat transfer coefficients along the outer circular cylinder and inner triangular cylinder had aspect ratios of 1.2 and 2. The local Nusselt number on the outer circular cylinder reached a minimum value at $\theta = 180^\circ$ (Fig. 5), while the minimum local Nusselt number on the inner triangular cylinder occurred at $\theta = 0^\circ$ or 360° (Fig. 6). Yu et al. [157] also applied the finite volume method with CFD Fluent software to study heat transfer to liquid gallium flow in a concentric annular passage for the outer heated circular and inner triangular cylinders. The highest heat transfer improvement occurred at the base of the triangular top side as compared with the base of the triangular bottom side. Forced and mixed convection in the annulus between two horizontal confocal elliptical cylinders was numerically studied by Zerari and Groulx [158]. It was noticed that the heat transfer in natural convection enhanced with an increase in Grashof number.

2.1.3. Rotating cylinder/experimental studies

There are many studies that focused on the effect of a rotating inner or outer horizontal cylinder, or both, in a concentric annular passage, on heat transfer coefficients and velocity profiles for laminar and turbulent flow. Gasley [159] is a pioneer researcher of heat transfer characteristics of axial flow between rotating concentric cylinders using a modified electric motor with smooth or slot rotor. In the experiments, Gasley showed a decrease in heat transfer for laminar flow with a slot rotor compared to a smooth gap. Bjorklund and Kaye [160] performed a study of heat transfer to flow between concentric rotating cylinders. Tachibana et al. [161] presented research on heat transfer in an annulus with an inner rotating cylinder and obtained good agreement with the correlation proposed by Bjorklund and Kaye [160].

Table 1
The average *Nu* number for different *Ra* numbers and *Pr* numbers.

Ra	*Pr*	$\overline{Nu}$		
		Shi et al. [151]	Kuehn and Goldstein [152]	Shahraki [153]
2.38×10^3	0.716	1.320	1.38	–
9.50×10^3	0.717	1.999	2.01	1.9901
3.20×10^4	0.717	2.911	2.89	–
6.19×10^4	0.718	3.361	3.32	3.3092
1.02×10^5	0.718	3.531	3.66	3.6475

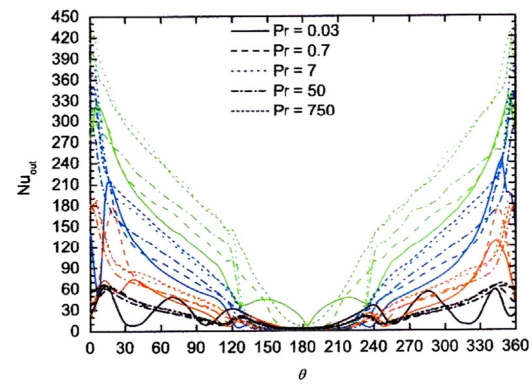


Fig. 5. Effect Prandtl number on Nusselt number along the outer circular cylinder at aspect ratio AR=1.2.

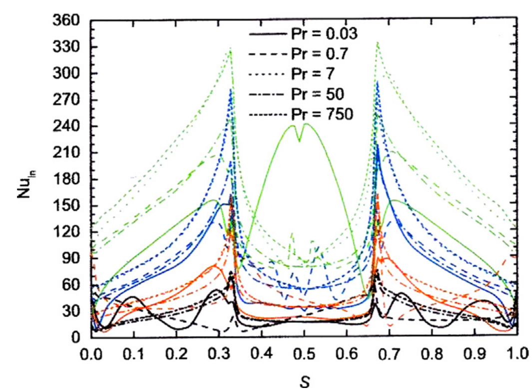


Fig. 6. Effect Prandtl number on Nusselt number along inner triangular cylinder at aspect ratio AR=1.2.

Koshmarov [162], Becker and Kaye [163], Kosterin and Finat'ev [164], Longobardo and Elrod [165], Tachibana and Fukui [166], Astill [167], and Aoki et al. [168] focused their investigations on the heat transfer and hydrodynamics in the gap between rotating cylinders with turbulent and laminar air flow. Some considered the effect of axial flow with vortex motion while others studied the heat transfer in an annular passage with no axial flow. Adequate agreement between experimental data and Becker and Kaye's [169] model was noted. Gardiner and Sabersky [170] experimentally studied heat transfer in the annular gap between an inner, rotating cylinder and an outer, stationary one with Prandtl numbers of 2.5, 4.5, and 6.5, Reynolds numbers of 800, 2700, and 7000 and Taylor numbers (*Ta*) up about 106. They obtained increased heat transfer coefficient for a slotted rotor in comparison to a smooth one. Investigations related to the effect of a rotating cylindrical annular on heat transfer at different boundary conditions was continued by Lee [171,172], and Hayase et al. [173].

Hamakawa et al. [174] presented an experimental study of heat transfer to water flow in a concentric cylinder, whereby the outer cylinder is stationary and the inner cylinder with cavities is rotating. They noticed the effect that the cavities have on fluid heating and behavior. They additionally observed that the amount

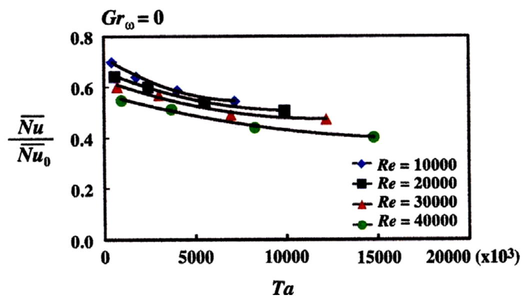


Fig. 7. Variation of at zero-buoyancy conditions with *Ta* at different Re.

of heat transferred to the inner cylinder with cavities is greater compared to that without cavities.

Chang et al. [175] also empirically studied the influence of rotating cylinders and Reynolds number on the Nusselt number value in a concentric annular channel. They noted that the local and average Nusselt number increased with decreasing Taylor and Reynolds numbers (Fig. 7).

Fenot et al. [176] presented experimental results of convective heat transfer in an annular cylinder with inner rotating cylinder. PIV measurement was used in the experiment and they demonstrated that axial and rotational speeds influenced local heat transfer. Heat transfer to air flow in a non-annular channel between rotor and stator with peripheral grooves was empirically assessed by Ahmadbadi and Karrabi [177]. They concluded that the heat transfer of the rotor and stator increased by 45 and 30% respectively, with increasing rotor revolution from 300 rpm to 1500 rpm. It was also noticed that the axial distribution of local heat transfer coefficient on the rotor's surface was more uniform compared to the surface of the rotor.

2.1.4. Rotating cylinder/numerical studies

Becker and Kaye [169] studied the effect of an inner rotating cylinder in an annular passage on the temperature gradient and instability of fluid flow. The Nusselt number was defined by Eqs. (4)–(6).

$$Nu = 2 \quad \text{For } Ta_m < 1700 (\text{laminar flow}) \tag{4}$$

$$Nu_B = 0.0128 Ta_m^{0.367} \quad \text{For } 1700 < Ta_m < 10^4 \tag{5}$$

$$Nu_B = 0.409 Ta_m^{0.241} \quad \text{For } 104 < Ta_m < 10^7 \tag{6}$$

where

$$Ta = \frac{\rho^2 \Omega^2 r \delta^3}{\mu^2} \tag{7}$$

For additional information regarding the impact of a rotating cylinder in an annular channel on heat transfer, a number of research works applied different numerical methods and experiments, for instance Nouar et al. [178]. They performed both numerical and experimental studies of incompressible Herschel–Bulkley fluid thermal convection in a horizontal concentric annular cylinder with a rotating adiabatic inner cylinder and heated outer cylinder. The effect of thermodependency on heat transfer at increased inner cylinder rotational velocity was demonstrated. Mahmoud and Fraser [179] applied the first and second laws of thermodynamics to examine heat transfer and fluid flow in an annular passage with rotating outer and inner cylinders. It was evident that at high temperature and velocity gradients, the entropy generation rate was greater and an asymptotic behavior towards the outer cylinder was noted. Liu and Lu [180] employed large eddy simulation (LES) of turbulent flow with a rotating inner cylinder in an annular passage. Yoo [181–186] carried out numerical studies of natural and mixed convection in a horizontal concentric annular passage with rotating cylinder for a range of Grashof, Rayleigh, and Prandtl numbers. A rising Prandtl number increases the critical Rayleigh number and heat transfer improves further at unicellular flow in comparison to bicellular flow. Teamah et al. [187] numerically examined the mixed convection between two horizontal concentric cylinders, for a rotating cooled outer cylinder and heated inner cylinder for different boundary conditions. They obtained a correlation between the Rayleigh, Prandtl and Reynolds numbers to calculate the average Nusselt as shown in Eq. (8). The Nusselt number increased with increasing Prandtl and Reynolds numbers and the same Rayleigh number.

$$Nu_i = 0.0166 Re_a^{0.336} Pr_B^{-0.008} Re^{-0.1263} \tag{8}$$

Al-Amiri and Khanafer [188] employed the Galerkin weighted residual method to analyze the mixed convection in a two-dimensional, horizontal, annular cylinder with rotation. Good agreement was obtained with observations of Yoo [181] regarding streamlines and isothermals (Fig. 8). Teamah [189] used the Patankar–Spalding technique to solve equations of continuity, momentum, energy and mass transfer for laminar mixed convection flow. The correlation between buoyancy ratio (N) and Rayleigh number (Ra) was found to calculate the Nusselt number using Eqs. (9) and (10).

For $N > 0$

$$Nu_{av} = 0.0185 Ra_T^{0.257} N^{0.21} \tag{9}$$

For $N < -1$

$$Nu_{av} = 0.0137\, Ra_T^{0.256} |N|^{0.32} \tag{10}$$

Hsu [190] applied the finite difference method with reverse matrix to simulate the thermal performance and viscosity of fluid flow in horizontal concentric cylinders with a rotating inner cylinder. The numerical results indicated a straight prediction of thermal behavior, viscosity and heat flux to fluid flow. Assad and Oztop [191] numerically studied entropy and internal heat generation between two rotating cylinders in convective surface cooling. According to outcome, the lower entropy generation amplified with the increase of both temperature ratio and Biot number, and it decreased with the increase of Brinkman number. Dellil and Azzi [192] used a code CFX1 and SST model to numerically study the turbulent heat transfer between rotor and stator. Three cases were adopted in the investigation according to rotation speed of the rotor and magnetic gap value. It was remarked that the heat transfer to the rotor rises with increasing air gap and number of revolutions. Kumar et al. [193] numerically studied the unsteady flow in a porous medium induced by periodically rotating a half-filled horizontal concentric passage. The study dealt with water and air, where the heat transfer rate was perceived to increase at greater aspect ratio at the surface of the inner cylinder, and it decreased with the increase of aspect ratio on the surface of the outer cylinder.

2.2. Heat transfer and fluid flow in vertical concentric annular passage

A great number of studies concentrate on the augmentations of heat transfer to liquid–solid, immiscible liquids, and liquid–gas flow in a vertical concentric annular passage. The majority of such investigations are related to the two-phase flow in a vertical concentric annular space, as reported by Leib et al. [194], Mizushina et al. [195], Michiyoshi et al. [196], Hassan et al. [197], Fossa et al. [198], Ozbelege and Koker [199], Fu and Klausner [200], Koizumi et al. [201], Ozbelge [202], Qiu et al. [203], Eraslan and Ozbelge [204], Li et al. [205], Kim et al. [206], Hetsroni et al. [207], Kim et al. [208,209], Bae and Kim [210], Bae [211], Davis and

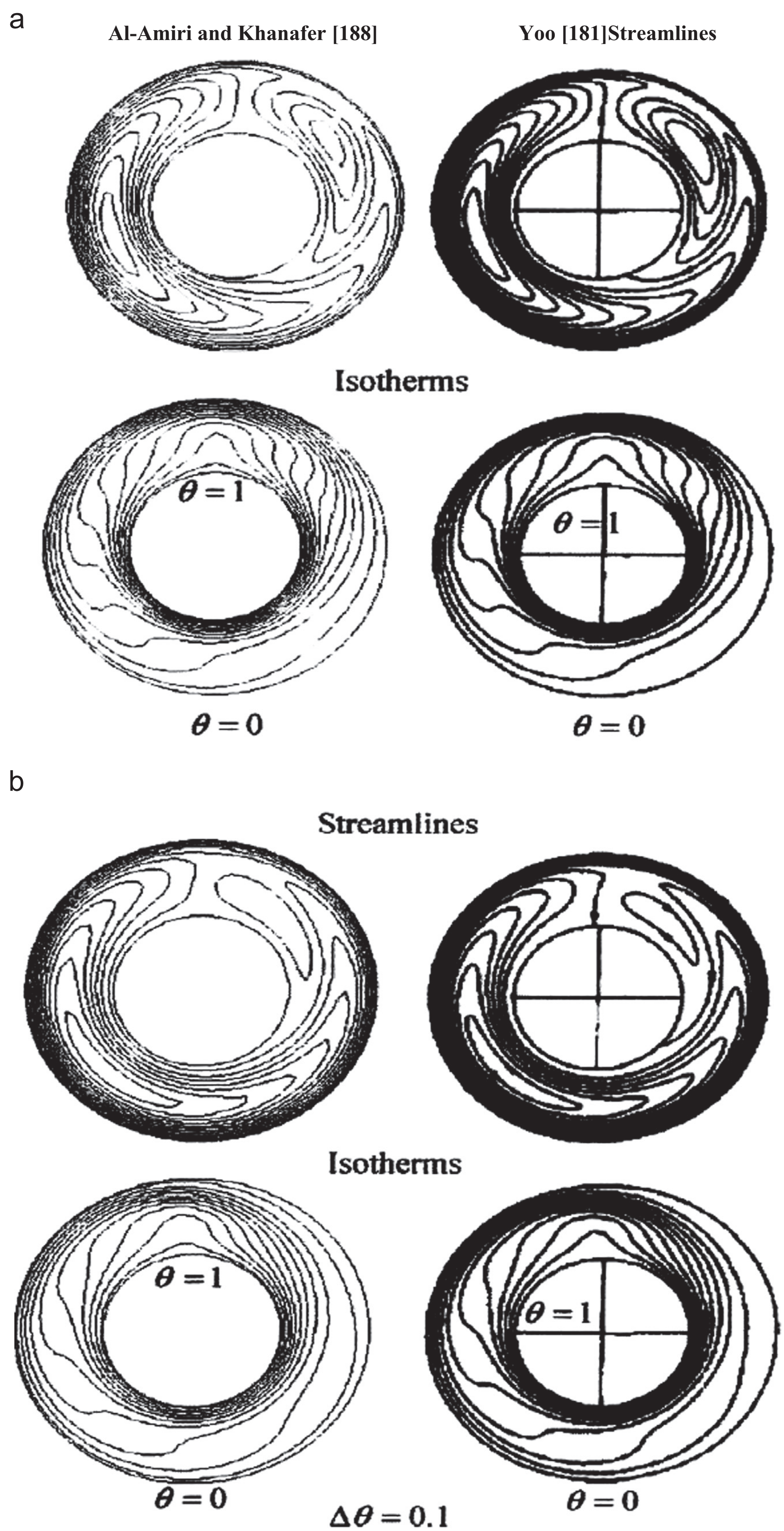


Fig. 8. Comparison of the streamlines and isothermals between Al-Amiri and Khanafer [188], and Yoo [173].

Thomas [212], Schwab and Witt [213], Maitra and Raju [214], Al-Arabi et al. [215], Hessami et al. [216], Iannello et al. [217], Yan and Tsay [218], Ho and Tu [219], Tasnim and Mahmoud [220], Usmani et al. [221], Lee [222], and Changhong et al. [223]. In these studies, focus was mainly directed toward the impact of aspect ratio, heater length, and Prandtl, Reynolds, Darcy and Rayleigh numbers

on the heat transfer process. As such, it was noted that thermal performance increased but required low-cost energy. Natural heat transfer in a vertical annular channel with porous medium was examined by Havstad and Burns [224], Reda [225], Prasad and Kulacki [226], Hickox and Gartling [227], Prasad et al. [228], Prasad [229], Lauriat and Prasad [230], Khan and Kumar [231], Chang and Hsiao [232], Hasnaoui et al. [233], Marpu [234], Char and Lee [235], Amara et al. [236], Shivakumara et al. [237], Kiwan and Alzahrani [238], and Barletta et al. [239]. The respective researchers conducted analyses of heat transfer and flow in a vertical porous annular space by employing numerical methods and experiments for various configurations in a vertical annulus having either closed or open ends.

2.2.1. Stationary cylinder/experimental studies

El-Shaarawi and Sarhan [240,241] and Oosthuizen and Paul [242] conveyed the results of experimental and numerical studies of natural convection fluid flow in a heated vertical annular passage, which facilitate good understanding of the velocity profiles and temperature distributions. Wrobel et al. [243] experimentally and numerically analyzed thermo-magnetic convection flow in a vertical concentric annular channel. The results showed higher heat transfer rate with the increase of magnetic force as opposed to rising thermal Rayleigh number. Also, good accord was evident between experimental and numerical data.

For clarity, we have selected some brief investigation observations made by Mizushina et al. [244], who performed experimental works on the effect of radial electric field on heat transfer and longitudinal pressure drop of laminar flow in a concentric annular passage using dielectric organic liquid. Apparently heat transfer increased with increasing electric field and furthermore, greater pressure drops of liquids with lower Prandtl number were identified. Michiyoshi et al. [245] experimentally investigated the local properties and heat transfer to mercury–argon two-phase flows with small gas flow and transverse magnetic at vertical annulus. The experimental data indicated a decrease in the two-phase Nusselt number with increasing single phase mercury heat transfer. Ozbelge [246] presented experimental data of heat transfer to water–slurry flow in a vertical annular passage, where the slurry flowed in an annular space while the water flowed through the inner pipe. A dimensionless group (d_p ∧ ∗=(d_p/(D_h)) Re_s ∧ (11/6)) equal to 4.2 was presented for water–slurry flow in a vertical annular passage, whereby heat transfer augmented to a maximum value. These results were compared with data presented by [247–251] as shown in Fig. 9. Hetsroni et al. [252] performed an experimental study of heat transfer to R12 flow in a vertical annular passage and focused on the effect of surfactant concentration. A maximum increase of heat flux to surfactant solution was noted with an increase in annular space width. They also perceived that the surfactant solution concentration ($C/C^{\circ}=1$) yielded a maximum heat transfer value. Bae and Kim [253] reported a set of experimental investigations on the study of convection heat transfer and CO_2 flowing through a tube and a vertical annular channel. They developed Nusselt number expressions for flow in a tube as per Eqs. (11)–(13) and for flow in an annular channel with Eqs. (14) and (15).

For upward flow in tube

$$f = (1-8000Bu)^{0.5} \quad \text{For } Bu < 1.0 \times 10^{-4} \tag{11}$$

$$f = 15Bu^{0.38} \quad \text{For } Bu > 1.0 \times 10^{-4} \tag{12}$$

For downward flow in tube

$$f = (1+30,000Bu)^{0.3} \quad \text{For all } Bu \tag{13}$$

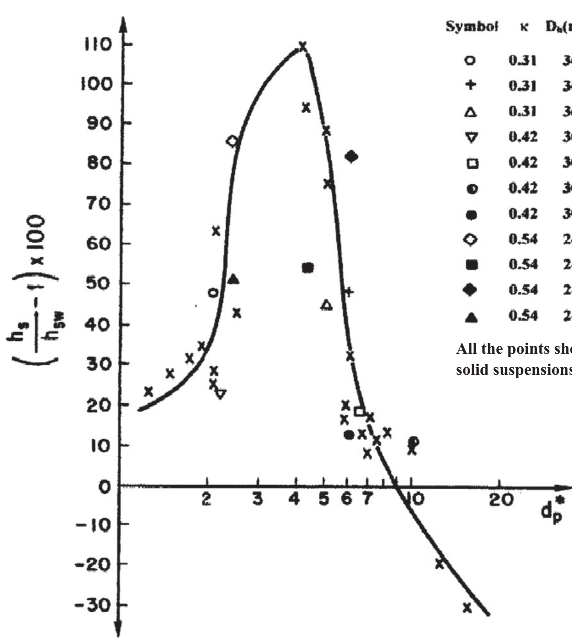
For upward flow in annular channel

$$f = (1-10,000Bu)^{1.5} \quad \text{For } Bu < 5.0 \times 10^{-5} \tag{14}$$

For downward flow in annular channel

$$f = (1-5000Bu)^{1.5} \quad \text{For } Bu > 5.0 \times 10^{-5} \tag{15}$$

Further in depth, Gang et al. [254] have experimented with measuring the surface temperature of an inner pipe in a vertical annular passage with supercritical water flow. The results signified greater heat transfer coefficient enhancement for annular space with 6 mm gap as compared with annular space of 4 mm. Malik et al. [255] did an experimental study of conjugate heat transfer through the bottom of a heated vertical concentric cylinder enclosure. The test experiment consisted of two cylinders with three different materials, and the inner cylinder was shorter and opened at the top. The highest axial and radial temperatures were obtained for stainless steel compared to aluminum and mild steel.



Symbol	κ	D_h(mm)	d_p(mm)	C_f (% wt)	Re_s	$[(h_s/h_{sw})-1]$
○	0.31	36	0.072	1.25	24000	0.48
+	0.31	36	0.127	1.25	53400	0.49
△	0.31	36	0.191	2.50	22400	0.45
▽	0.42	30	0.072	0.75	21200	0.23
□	0.42	30	0.127	2.50	47000	0.20
◉	0.42	30	0.191	1.25	47200	0.12
●	0.42	30	0.191	0.75	21600	0.13
◇	0.54	24	0.072	2.50	16400	0.86
■	0.54	24	0.127	0.75	17250	0.55
◆	0.54	24	0.191	2.50	15600	0.83
▲	0.54	24	0.072	1.25	17450	0.52

All the points shown with 'x' represents the data for pipe flows of liquid-solid suspensions [247,248,249,250,251]

Fig. 9. Locations of $\overline{Nu}/\overline{Nu}_o$ peak heat transfer enhancement for water-feldspar upward flows through vertical annuli.

2.2.2. Stationary cylinder/numerical studies

Prakash and Renzoni [256] conducted a numerical investigation of laminar, fully developed flow in a vertical concentric circular annular duct with radial internal fins. Buoyancy appeared to increase both friction and heat transfer. Mohanty and Dubey [257] also conducted numerical and experimental investigations of buoyancy-induced flow and heat transfer in a vertical annular passage. Good agreement was attained between experimental and numerical data, especially for local Nusselt numbers. Eraslan and Ozbelge [258] numerically analyzed heat transfer to laminar water-slurry flow in a vertical annular passage and compared it with previous experimental data reported by Ozbelge [204]. It was seen that a maximum heat transfer improvement ratio occurred with minimum Reynolds numbers of the slurry (Fig. 10).

Reddy and Narasimham [259] numerically studied the natural convection with a heated inner rod in a vertical annular passage. Apparently, an increasing Grashof number leads to an increasing trend in average Nusselt number (Fig. 11) and a good agreement was also noticed between the presented Nusselt numbers and Farouk et al.'s results [260] (Table 2). Chen et al. [261] employed the lattice Boltzmann method to study natural convection and entropy generation in a vertical concentric annular passage. They inferred that due to the increase in curvature ratio and Rayleigh number, the maximum of number entropy generation skips to the outer wall. Additionally, a good agreement with Schwab and Witt's results [213] was obtained, as shown in Table 3.

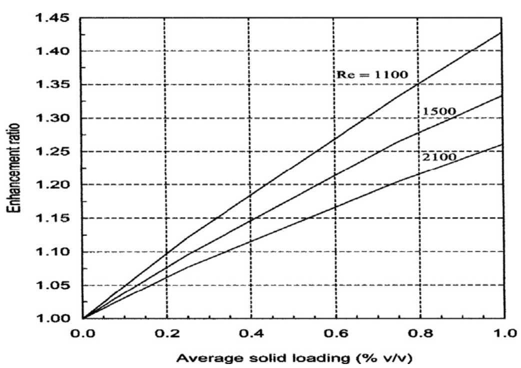


Fig. 10. Enhancement ratio vs. $\overline{\varnothing}_s$ values at different Reynolds numbers for T_{in}= 50 °C and T_{W1}=10 °C.

Table 2
Comparison of Nusselt number obtained by Reddy and Narasimham [267] with Farouk et al. [268] at the differentially heated annulus for $Gr=10^5$ and $k=2$, PD=Percentage difference.

H*	Pr=0.07			Pr=0.7			Pr=7.0		
	Ref. [260]	Ref. [259]	PD	Ref. [260]	Ref. [259]	PD	Ref. [260]	Ref. [259]	PD
0.5	1.10	1.09	0.91	3.10	2.88	7.10	7.70	7.65	0.65
1.0	1.75	1.71	2.29	3.50	3.74	6.86	8.10	7.70	4.94
5.0	1.50	1.51	0.67	3.15	3.14	0.32	5.70	5.85	2.63

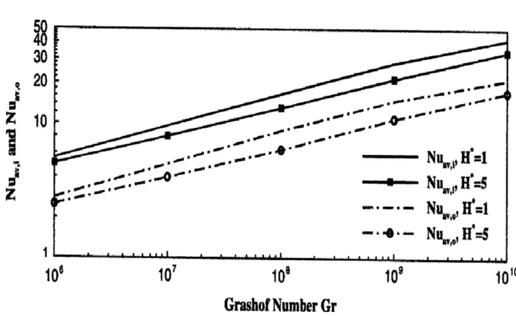


Fig. 11. Variation of $Nu_{av,i}$ and $Nu_{av,o}$ with Grashof number for $\lambda^*_s=5$ and $k=2$.

To further augment heat transfer, Mina et al. [262] performed a numerical study on the natural convection heat transfer rate in vertical annular channels with nanofluid copper-water. By using the finite volume method with FORTRAN software, the analysis equations signified an increase in Nusselt number with increasing solid concentration of nanofluid; the maximum Nusselt number was attained when the inclined annular channel angle equaled zero degrees. Result validation was reached by comparing the Nusselt number values with Guja and Stella [263] and Davis and Thomas' results [212].

Reddy and Narasimhan [264] completed a numerical study of two-dimensional heat generation in the natural convection inside a porous annulus by utilizing the two energy equations of the local thermal non-equilibrium (LTNE) model combined with the generalized porous medium momentum equation based on the finite volume method. They obtained a correlation for the average Nusselt number between cold and hot walls through eq. (16). Sankar and Do [265] and Sankar et al. [266] conducted a numerical study of natural convection in a vertical concentric annular cylinder filled with a fluid-saturated porous medium. They used the Brinkman-extended Darcy equation with the implicit finite difference method to solve the governing equations for a wide range of Darcy and modified Rayleigh numbers. They obtained augmented average Nusselt number with increased porosity and Darcy number values. They also obtained good agreement with Waheed's outcome [267] in terms of average Nusselt number (Table 4).

$$\overline{Nu} = \frac{-1}{(1-\phi)\gamma+\phi}\left[(1-\phi)\gamma\int_0^1 \frac{\partial\theta_s}{\partial r^*}dz^* + \phi\int_0^1 \frac{\partial\theta_f}{\partial r^*}dz^*\right] \tag{16}$$

The laminar natural convection between vertical coaxial rectangular cylinders was numerically studied by Gavara and Kanna [268]. They observed that at the inner cylinder, the local Nusselt number increased towards the cylinder edges; the increase in

Table 3
Comparison of average Nusselt number presented by Chen et al. [261] with Schwab and Witt [213].

Pr	Ref. [211]	Ref. [220](100 × 100)	Ref. [220](200 × 200)
0.73	6.13	6.1342	6.1352
1.0	6.17	6.1690	6.1673
7.0	6.36	6.3577	6.3721
25.0	6.31	6.3200	6.3259

Table 4
Comparison of average Nusselt number reported by Sankar et al. [266] with Waheed [267] at a uniformly heated rectangular porous cavity ($A=1$, $\lambda=1$, $\phi=1$and $Pr=0.71$).

Rayleigh number (Ra)	Darcy number (Da)	Waheed [267]	Sankar et al. [266]
10^4	10^{-3}	1.0301	1.0321
	10^{-2}	1.5849	1.5862
	10^{-1}	2.1526	2.1552
10^5	10^{-3}	2.0940	2.1304
	10^{-2}	4.0634	4.0812
	10^{-1}	4.4915	4.5216
10^6	10^{-3}	6.6452	6.7521
	10^{-2}	8.5284	8.6340
	10^{-1}	8.7564	8.8721

average Nusselt number was about 2.5 times at the bottom face compared to all other faces.

Recently Mahian et al. [269] used entropy generation analysis with MHD flow for the design of a vertical heat exchanger. Three radius ratios (R) were adopted, where $R=2$ represents the base after which the energy cost was calculated at $R=1.9$ and 2.1. An increase in energy cost of about 17.5% at $R=1.9$ resulted as well as decreased coat of energy of roughly 13.6% at $R=2.1$ compared to $R=2$.

2.2.3. Rotating cylinder/experimental studies

Kuzay and Scott [270] investigated experimentally the turbulent heat transfer to fluid flow in a vertical concentric annular channel with and without a rotating inner cylinder. They obtained good correlation between rotational and non-rotational Nusselt number and friction coefficient. Mixed convection heat transfer in vertical concentric annular cylinders with a rotating heated inner cylinder while the outer cylinder was stationary and cooled, was empirically studied by Ball et al. [271]. They observed the effect of secondary flow created by rotating the inner cylinder on heat transfer rate in an annular passage. Kim and Hwang [272] presented the experimental results of vortex flow in a vertical concentric cylinder with a stationary outer cylinder and rotating inner cylinder. The outcome refers to the relation between Rossby number and Reynolds number with respect to the skin friction coefficient. It was apparent that the increase of rotational speed of the inner cylinder leads to a decrease of fluid flow Reynolds number.

El-Maghlany et al. [273] also experimentally studied the performance characteristics and fluid flow through a vertical heat exchanger with a rotating inner pipe. They obtained good correlations between computation properties of water and found an increase in heat transfer rate due to higher rotation speed and Reynolds number.

2.2.4. Rotating cylinder/numerical studies

El-Shaarawi and Sarhan [274] numerically studied the effect of a rotating inner cylinder in a vertical annulus on heat transfer of forced and free laminar convection at the entrance region using a finite difference scheme. Leonardi et al. [275] further numerically assessed heat transfer in a vertical rotating annulus. They obtained the Nusselt number, velocity and temperature profiles as a function of the Prandtl, Reynolds and Rayleigh numbers. Khellaf and Lauriat [276] presented a numerical investigation of the natural and mixed convection heat transfer in a Non-Newtonian Carreau-fluid between rotating concentric vertical cylinders. The results indicated the effect of shear thinning on the decreasing friction factor at the rotating inner cylinder and increasing heat transfer in the annular gap. In a numerical study by Venkatachalappa et al. [277] on natural convection, heat transfer in a vertical annular cylinder was observed and the outcome revealed the effect of rotational flow and aspect ratio on heat transfer rate in the cylinder. Chung and Sung [278] used large eddy simulation to examine the effect of the rotating inner pipe in vertical annular pipe and buoyancy on the turbulence structure near the wall with mixed convection. They observed a decline in turbulent statistics by the rotating inner pipe, and also that reduction occurred in turbulence intensity and shear stress with a stationary inner cylinder. Amour et al. [279] and Zeraibi et al. [280] adopted a numerical study of convection heat transfer to thermo-dependant Non-Newtonian fluid flow in a vertical concentric annular passage with heated rotating inner cylinder. They identified a higher increase in Nusselt number with an increase of Reynolds number at $Ra=1000$ for fluid thermo-dependant than with the fluid non thermo-dependant (Fig. 12).

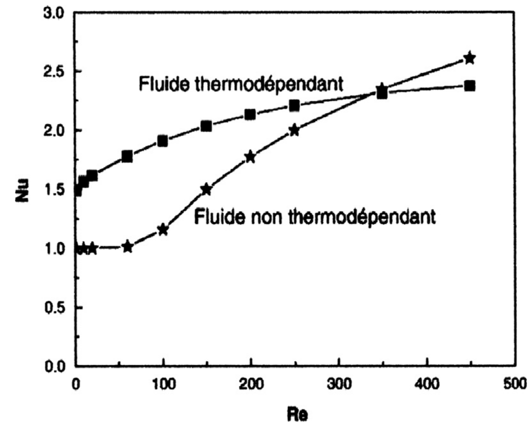


Fig. 12. Average Nusselt number as a function of the Reynolds number for a thermodependent and non thermodependent fluid at $Ra=1000$.

3. Heat transfer and fluid flow in eccentric annular passage

The fluid flow and heat transfer in an eccentric annular passage is found in a variety of engineering applications. Therefore, many researchers have implemented numerical and experimental studies to analyze heat transfer and fluid flow with different boundary conditions in an eccentric annular passage (Bory and Faure [281], Heyda [282], Snyder [283], Jonsson and Sparrow [284], Snyder and Goldstein [285], Yu and Dwyer [286], Cheng and Hwang [287], Thrombetta [288], and Feldman [289], Projahn et al. [290], Cho et al. [291], Bau [292], Projahn and Beer [293], Ho et al. [294], Naylor et al. [295], Choudhury and Karki [296], Raghavarao and Sanyasiraju [297], Mota and Saatdjian [298], Shu et al. [299], and Lee et al. [300]). The mentioned studies were performed to identify the effect of eccentricity, Prandtl number and Rayleigh number on heat transfer rate in horizontal eccentric annular channels.

3.1. Heat transfer and fluid flow in horizontal eccentric annular passage

3.1.1. Stationary cylinder/experimental studies

Miaev et al. [301] experimentally studied the natural convection heat transfer and water flow in a horizontal eccentric annular duct. Grashof numbers, Reynolds numbers, eccentricity and radii ratios were presented against heat transfer data. An increase of Nusselt number was noted with enhanced free convection.

Guj and Stela [263] presented new experimental data on heat transfer between horizontally eccentric cylinders. The experiment was conducted at $1.07\times104 \le RaL \le 8.27\times104$ and at a wide eccentricity range. They found that the Nusselt number was affected by eccentricity rather than concentric geometry. Hirose et al. [302] also experimentally and numerically studied fluid flow and heat transfer in a horizontal eccentric annular passage with unheated inner circular cylinder and heated outer elliptical cylinder. They showed the effect of oriented angle and eccentric configuration on heat transfer enhancement.

Recently, experimental and numerical research on two-phase flow in horizontal eccentric annuli was reported by Sorgun et al. [303]. Experimentation was done in air–water mixtures at different velocities and a high-speed camera was used to record flow patterns, while the numerical study employed an Eulerian computational fluid dynamics model for gas–liquid flow in the annuls. Adequate accord between experimental and numerical data was obtained and the effect of eccentricity on flow patterns for all cases was noted. Wang [304] performed experimental and numerical investigations into the natural convection heat transfer in

horizontal annuli between eccentric cylinders. The numerical study used the finite difference method with a central difference approach and a Mach–Zehnder interferometer was employed for the experimental study. The agreement from the comparison between experimental and numerical results was good.

3.1.2. Stationary cylinder/numerical studies

Suzuki et al. [305] performed a numerical computation to estimate the laminar forced convection heat transfer in eccentric annuli. They employed two types of the second kind of thermal boundary condition and calculated the average Nusselt number and friction coefficient. Manglik and Fang [306] presented numerical solutions for the effect of eccentricity and thermal boundary conditions on laminar, fully developed flow in annular ducts by applying the finite differencing strategies adopted by Prusa and Yao [307] and Manglik and Bergles [308]. A decrease in Nusselt number was found with an increase in eccentricity, while the velocity profiles were sharp with peak velocities and higher gradient in the widest end of the annular passage at angular coordinates ($\psi = 180^{\circ}$). Good agreement was also found with Shah and London's results [309]. El-Shaarawi et al. [310] performed a numerical study of developing laminar forced convection heat transfer in an eccentric annular passage at the entry region by using finite difference numerical method with a boundary layer model. They obtained a decrease in mixed mean temperature and a pressure drop with increased eccentricity while the global Nusselt number and local circumferentially average Nusselt numbers increased on the inner and outer walls of the annular pipe. They also attained good agreement with Feldman et al.'s study [311,312].

Monterio et al. [313] presented a numerical work on the effect of eccentricity on convective heat transfer and laminar fluid flow for Non-Newtonian fluids in doubly-connected ducts by using hybrid numerical–analytical solutions with a generalized integral transform technique. They dealt with two cases, of which the first involved an internal heated wall while the external wall was insulated, and in the second case, the internal wall was insulated and the external wall was heated. The results of the first case revealed that the Nusselt number increased with a decrease in eccentricity and in the second case the Nusselt number decreased with increased eccentricity (Table 5). This refers to the behavior of the local Nusselt number for eccentric ducts with different power-law indicates, eccentricities and radii ratios, which is in good agreement with Viana et al. [314], Manglik and Fang [315], and Nascimento et al. [316] with respect to Nusselt number.

Merzari and Ninokata [317] numerically assessed the inhomogeneous turbulent shear flow in eccentric annular channels using the LES method. It was demonstrated that at high Reynolds numbers the secondary flow effect on anisotropy and shape of secondary flow depend on eccentricity. Fattahi et al. [318] employed Lattice Bolthzman simulation in a study of mixed convection heat transfer in an eccentric annulus. They observed the effect of eccentricity on heat transfer where the average Nusselt number increased with the inner cylinder moving downward regardless of radial position. They computed the average of corresponding heat conductivity with inner and outer cylinders in Eqs. (17, 18) and compared their results to data of Kuehn and Goldstein [29]. The streamlines at the top and isothermals at the bottom were contrasted against experimental data by Guj and Stela [263] (Fig. 13). Ait et al. [319] carried out a numerical study on the influence of Buoyancy forces and different eccentricities on the rheological behavior of fluid flow and thermo-dependency by employing the finite different method. The results obtained signify that the select suitable eccentricity value depends on the fluid's thermal and rheological properties.

$$\overline{K}_{eqi} = -\frac{\ln(rr)}{\pi(rr-1)}\int_0^{\pi}\frac{\partial T}{\partial r}\cdot d\varphi \tag{17}$$

Table 5
Convergence behavior of the local Nusselt number expansions for eccentric annular ducts with different power-law indices, radii ratios and dimensionless eccentricities.

$NT=NT^{*}$	$Nu(z)$					
	Case A			Case B		
	$n=0.5$,	$n=1$,	$n=1.5$,	$n=0.5$,	$n=1$,	$n=1.5$,
	$\gamma=0.8$, $\varepsilon=0.6$	$\gamma=0.5$, $\varepsilon=0.2$	$\gamma=0.2$, $\varepsilon=0$	$\gamma=0.8$, $\varepsilon=0.6$	$\gamma=0.5$, $\varepsilon=0.2$	$\gamma=0.2$, $\varepsilon=0$
	$Z=10^{-4}$					
5	14.930	22.371	32.954	12.930	13.363	9.8819
10	20.155	30.131	32.183	17.574	21.918	16.946
15	22.365	28.561	31.832	20.088	25.494	22.212
20	22.737	27.823	31.792	21.212	25.914	25.009
25	22.356	27.844	31.793	21.462	25.435	25.594
30	21.966	27.840	31.785	21.274	24.942	25.001
35	21.806	27.826	31.785	20.986	24.686	24.287
40	21.790	27.816	31.782	20.776	24.608	23.907
	$Z=10^{-2}$					
5	3.9667	7.0572	9.8155	12.930	13.363	9.8819
10	3.8732	7.0378	9.7023	17.574	21.918	16.946
15	3.8718	7.0407	9.7149	20.088	25.494	22.212
20	3.8705	7.0393	9.7106	21.212	25.914	25.009
25	3.8704	7.0397	9.7125	21.462	25.435	25.594
30	3.8701	7.0394	9.7115	21.274	24.942	25.001
35	3.8701	7.0394	9.7121	20.986	24.686	24.287
40	3.8701	7.0394	9.7117	20.776	24.608	23.907
	$Z=1$					
5	1.2594	3.7054	8.0802	1.1370	2.8766	4.2089
10	1.2517	3.7051	8.0787	1.1299	2.8766	4.2087
15	1.2517	3.7051	8.0787	1.1299	2.8766	4.2087
20	1.2517	3.7051	8.0787	1.1299	2.8766	4.2087
25	1.2517	3.7051	8.0787	1.1299	2.8766	4.2087
30	1.2517	3.7051	8.0787	1.1299	2.8766	4.2087
35	1.2517	3.7051	8.0787	1.1299	2.8766	4.2087
40	1.2517	3.7051	8.0786	1.1299	2.8766	4.2087

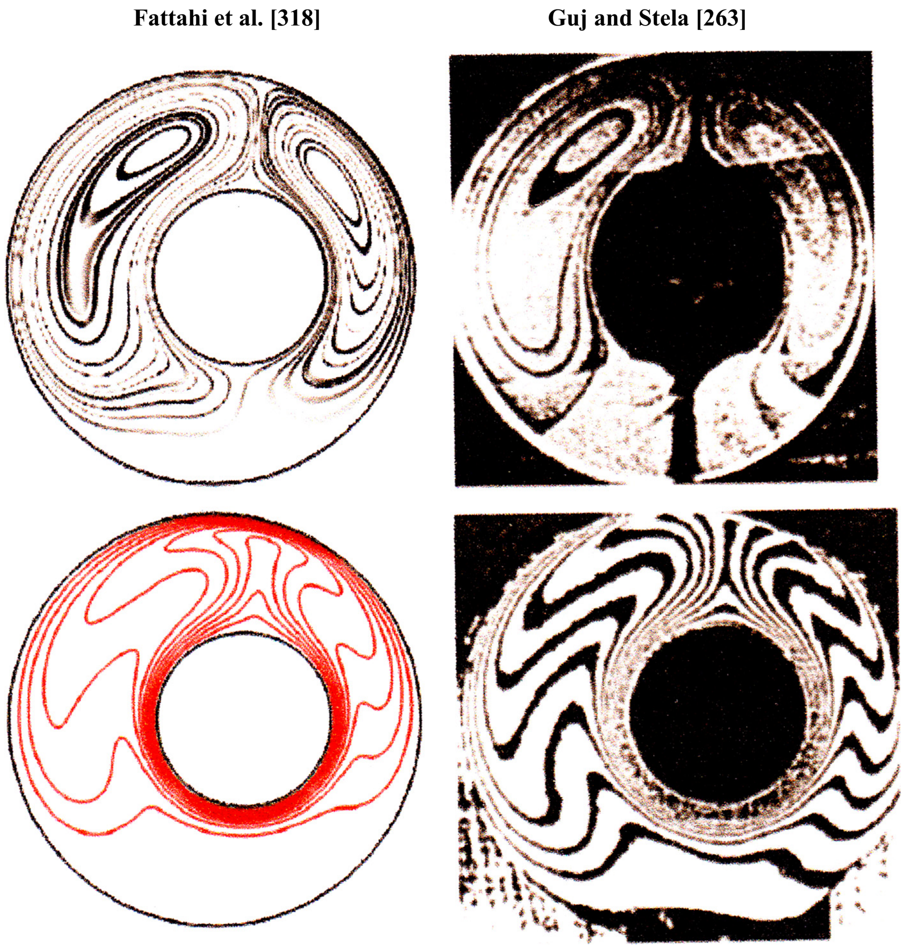


Fig. 13. Comparison of streamlines (top) and isotherms (bottom) for $\varepsilon=(1/4, -\pi/2)$, $Ra=4.59\times104$ between Fatthi et al. [318] and Guj and Stella [263] using $\sigma=1.47$.

$$\overline{K}_{eqo} = -\frac{rr\ \ln(rr)}{\pi(rr-1)}\int_0^{\pi}\frac{\partial T}{\partial r}\cdot d\varphi \tag{18}$$

Cheng and Chao [320] performed a numerical study of heat transfer and fluid flow in a horizontal eccentric annular passage with inner and outer elliptical annular. Significant improvement in heat transfer rate was observed due to the buoyancy strength created by fluid motion. Mota et al. [321] used Darcy–Boussinesq equations to predict natural heat transfer to a saturated porous medium in a horizontal eccentric elliptic annulus. A greater enhancement of heat transfer was noted for the eccentric elliptical annular passage in comparison to the concentric annular passage and they also obtained a good agreement between predicted Nusselt number values and data obtained by Bau [292], Bau et al. [322] and Charrier-Mojtabi et al. [323] (Table 6). For a square-shaped passage, a study was performed by Shu et al. [324] who applied the differential quadrature (DQ) method to study the laminar boundary layer and heat transfer between the heated inner circular cylinder and unheated outer square cylinder. They calculated the average Nusselt number at the outer and inner cylinders using Eqs. (19, 20) where Si and So represent circumferential lengths for the two cylinders, and they used half values of Si and So in the equations as in a similar method presented by Moukalled and Acharya [61]. Ding et al. [325] used muliquadrics (MQ) and differential quadrature (DQ) to simulate convection heat transfer and fluid flow in a horizontal eccentric annular passage with a heated outer circular cylinder and unheated square outer cylinder. The numerical results from the MQ-method are more accurate compared with the DQ method and concur with the results reported by Shu et al. [324] (Table 7). Hussain and Hussain [326,327] presented a numerical study of mixed and natural heat transfer to air flow between an unheated square outer and heated inner circular cylinder. They observed a rise in Nusselt number with an increase in Rayleigh number at different inner cylinder positions and also obtained good agreement between the Nusselt number and results of Kim et al. [328] and Moukalled and Acharya [61] (Table 8).

$$\overline{Nu}_i = \frac{\overline{h}_i S_i}{K} \tag{19}$$

$$\overline{Nu}_o = \frac{\overline{h}_o S_o}{K} \tag{20}$$

Mahfouz [329] used the Fourier Spectral Method to study the free convection within an eccentric annulus filled with micropolar fluid. The heat transfer rate in the annulus decreased with increasing dimensionless material parameters of the micropolar fluid and also reported the effect of the Prandtl number, Rayleigh number and eccentricity on the Nusselt number. Mehrizi et al. [330] numerically studied the natural convection heat transfer to Cu-Water nanofluid flow in horizontal cylinder annuli with an inner triangular cylinder using the Lattice Boltzmann method. They found increased enhancement of heat transfer and stream functions with an increase in nanoparticle volume fraction, at the inner cylinder movement downward as well as a diminishing improvement of heat transfer with the inner cylinder movement

Table 6
Comparison of values of Nusselt number obtained by Mota et al. [321] with Bau [292], Bau et al. [322] and Charrier-Mojtabi et al. [323] for different numerical methods.

Ra	Ref. [292] Pade	Ref. [323] Fourier- Galerkin	Ref. [323] Collocation-Chebyshev	Ref. [322] Finite differences	Ref. [321] Finite differences
Two-cellular flow $\varepsilon \le 0.001$					
50	1.343			1.335	1.338
100	1.862			1.844	1.861
120		2.050	2.052		2.050
150	2.26			2.26	2.309
200	2.54	2.68	2.684	2.63	2.688
300		3.287	3.310		3.322
$\varepsilon = 0.2$					
50	1.293			1.288	1.292
100	1.765			1,743	1.764
200	2.59			2.462	2.550
$\varepsilon = 0.4$					
50	1.246				1.247
100	1.62			1.61	1.621
150	1.98			1.95	1.975
200	2.3			2.26	2.294
$\varepsilon = 0.6$					
50	1.199				1.198
100	1.479			1.465	1.479
150	1.744			1.69	
200	1.993			1.93	
$\varepsilon = 0.8$					
50	1.143				1.144
100	1.327			1.32	1.327
150	1.494			1.47	1.500
200	1.64			1.62	1.642
Four-cellular flow $\varepsilon = 0$					
120		2.266	2.261		2.272
200		2.90	2.907		2.921
300		3.48–3.56	3.55–3.70		3.520

Table 7
Comparison of ψ_{max}, ψ_{wall}, and $\overline{Nu}$ ($Pr = 0.71$) performed by Ding et al. [325] with Shu et al. [324] for eccentric annular and $Ra = 3 \times 10^5$.

φ°	ε	ψ_{max}		ψ_{wall}		$\overline{Nu}$	
		Ref. [325]	Ref. [324]	Ref. [325]	Ref. [324]	Ref. [325]	Ref. [324]
0°	0.25	18.64	18.67	$< 10^{-3}$	$< 10^{-4}$	6.74	6.75
	0.50	21.29	21.43	$< 10^{-3}$	$< 10^{-4}$	6.92	6.98
	0.75	23.52	24.07	$< 10^{-3}$	$< 10^{-4}$	7.63	7.95
45°	0.25	18.50	18.84	0.04	0.11	6.64	6.90
	0.50	20.03	19.75	0.46	0.47	6.68	6.92
	0.75	21.01	20.65	1.46	1.46	6.78	7.06
0.95	21.59	21.68	1.64	1.80	7.29	7.61	
90°	0.25	17.00	17.15	0.20	0.15	6.48	6.73
	0.50	16.97	18.77	0.94	1.64	6.42	6.72
	0.75	16.84	16.83	1.35	1.05	7.03	7.40
135°	0.25	15.32	15.56	0.21	0.12	6.29	6.48
	0.50	14.35	14.60	0.69	0.84	6.01	6.25
	0.75	13.61	13.94	1.19	1.25	5.96	6.23
0.95	12.98	12.96	1.29	0.93	6.36	6.45	
180°	0.25	12.39	12.55	$< 10^{-3}$	$< 10^{-4}$	6.74	7.05
	0.50	11.38	11.32	$< 10^{-3}$	$< 10^{-4}$	6.15	6.17
	0.75	10.09	10.26	$< 10^{-3}$	$< 10^{-4}$	6.62	6.90

Table 8
Comparison of average Nusselt number at the hot wall obtained by Hussain and Hussain [326] with Kim et al. [328] and Moukalled and Acharya [61].

Ra	Ref. [332]	Ref. [336]	Ref. [59]	Error (%)
10^4	3.4047	3.414	3.331	−2.2125
10^5	5.12893	5.1385	5.08	−0.96318
10^6	9.38875	9.39	9.374	−0.1573
10^7	15.6995	15.665	15.79	0.57314

horizontally. In contrast, Matin and Pop [331] presented a numerical study of the natural heat transfer to Copper (Cu) -water nanofluid flow in a horizontal eccentric annulus. They applied stream function vorticity formulation in polar coordinates in order to obtain high accuracy in the result on the effect of eccentric and volume friction of nanoparticles on Prandtl number and Nusselt number and obtained good agreement with previous investigations.

3.1.3. *Rotating cylinder/experimental studies*

There are numerous papers which adopted studies of a rotating cylinder in horizontal eccentric annular passages. Lee [332] presented numerical and experimental studies of fluid convection flow with air enclosed between horizontal eccentric annular cylinders with inner cylinder rotation. The results indicated a decrease in mean Nusselt number during the flow with rotating inner cylinder and fixed Ra. Nouri and Whitelaw [333] measured three components of velocity of Newtonian and a weakly elastic shear thinning parameter (Non-Newtonian fluid) in an annulus with eccentricity of 0.5 and rotating inner cylinder. The results showed that the rotation of the inner cylinder has the same effect on both Newtonian and Non-Newtonian fluid and the intensity of turbulence increases with rotation in Newtonian fluid but it decreases in Non-Newtonian fluid in a small gap. Escudier et al. [334] conducted an experimental and computational study of laminar, fully developed liquid in an eccentric annular with rotating inner cylinder. Wall shear stress, flow field, friction factor, Taylor number and radius ratio were computed in this study. They observed a significant effect on radial and tangential velocity and inner cylinder rotation on axial velocity distribution.

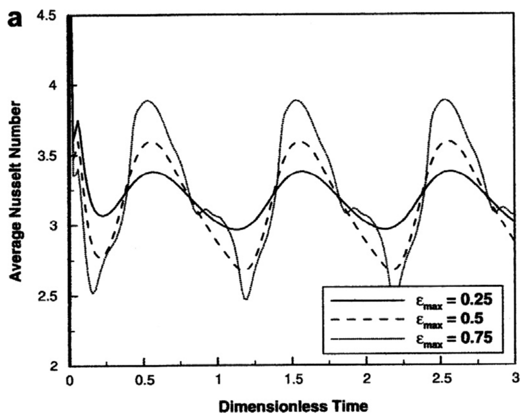


Fig. 14. Effect of oscillating eccentricity of the inner cylinder on the average Nusselt number at inner cylinder for $\Omega=1$, and $Ra=5\times10^4$.

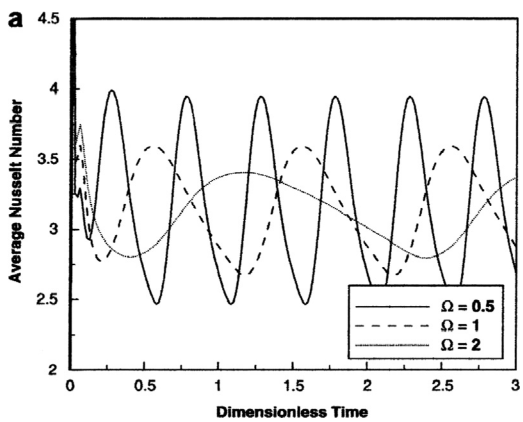


Fig. 15. Effect of oscillating frequency of the inner cylinder on the average Nusselt number at inner cylinder for $\varepsilon_{max}=0.5$, and $Ra=5\times10^4$.

3.1.4. Rotating cylinder/numerical studies

Abu-Sitta et al. [335] performed a numerical simulation of mixed convection heat transfer in horizontal counter rotating eccentric and concentric cylinders by adopting a finite element scheme based on the Galerkin method of weighted residuals. The numerical results indicated the effect of Rayleigh number, angular positions and eccentricity on the local Nusselt number. Alawadhi [336] used Lagrangian–Eulerian Kinematics with finite element method to study natural convection heat transfer in horizontal annular cylinders with a transversely oscillating inner cylinder. The numerical results indicate an increase in oscillations of average Nusselt number at the inner cylinder with increased oscillation eccentricity (Fig. 14). He also observed an increase in oscillation of average Nusselt number amplitudes with increasing oscillating frequency at the inner cylinder (Fig. 15). Jayanthi [337] used the finite difference method to study laminar Non-Newtonian flow through eccentric annuli with inner cylinder rotation. They showed the effect of radius ratio, eccentricity, and speed of inner cylinder rotation on flow pattern and friction factor, which is helpful to designing oil and gas drilling wells. In contrast, the moment and forces exerted on the inner cylinder in eccentric annular flow with rotating inner flow was numerically studied by Podryabinkin and Rudyak [338]. They found that the momentum exerted on the inner cylinder increased with the increase of eccentricity and also the effect of forces on the inner cylinder by pressure and viscous friction. The effects of axial and rotation motion of the inner cylinder of an eccentric horizontal annular channel with displacement flow between two different fluids were studied by Teja and Frigaard [339]. The results signify that due to rotation, the amplified interface decrease in the axial direction and in the azimuthal phase shifts away from the symmetric profile. Sorgun [340] conducted a numerical study of turbulent and laminar helical flow of Non-Newtonian fluids through concentric and eccentric annuli where the inner cylinder rotates. They obtained a decrease in friction pressure losses with the increase of inner pipe rotation for the laminar and turbulent range in concentric and eccentric annuli.

3.2. Heat transfer and fluid flow in vertical eccentric annular passage.

3.2.1. Stationary cylinder/experimental studies

Hosseini et al. [341] empirically studied the natural heat convection transfer in a vertical eccentric annular passage with a heated outer cylinder and unheated inner cylinder. Their experiment were covered for a single pipe, concentric annular, and eccentric annular passage, and the results were in good agreement with those of Al-Arabi et al. [215] for a single pipe. They also noticed greater improvement in heat transfer with an eccentric annular than in a concentric annular (Fig. 16). Hosseini et al. [342] also performed an experimental study of turbulent forced convection heat transfer in a vertical eccentric annulus with an outer tube at constant heat flux and insulated inner tube. They observed an increase in heat transfer coefficient with the increase of eccentricity. They also noted that heat transfer in eccentric annulus is higher compared to that in a concentric annulus and single tube (Fig. 17). Choueiri and Tavoularis [343] carried out an experimental investigation into the natural convection heat transfer in vertical open-ended concentric and eccentric annuli. They observed the effect of eccentricity on heat transfer rate and noticed that the heat transfer improved on one side of the annulus but it decreased on the other side. Maudou et al. [344] carried out an experimental study on mixed convection in vertical, open-ended, concentric and eccentric cylinders. The study focused on the effect of eccentricity on heat transfer in upward flow, and they showed a decrease in

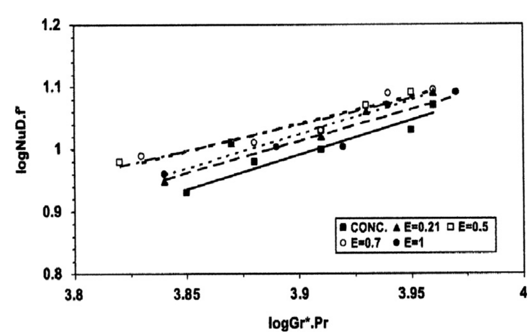


Fig. 16. Comparison of logarithmic variation of with log Gr^*_D. Pr for concentric and eccentric pipes.

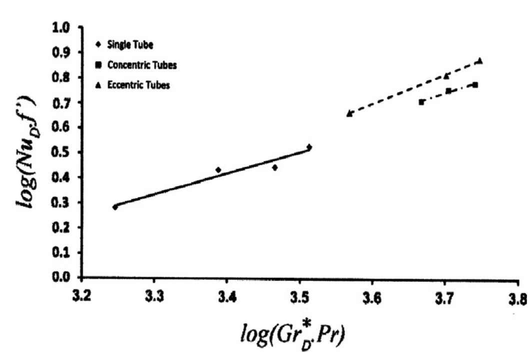


Fig. 17. Comparison of results of single tube, concentric annulus and eccentric annulus.

the average heat transfer rate of around 60% over high eccentricity. The Nusselt number was also lower in a highly eccentric cylinder as opposed to the concentric case.

3.2.2. Stationary cylinder/numerical studies

Sathyamurthy et al. [345] carried out a numerical study of laminar, fully-developed mixed convection flow in vertical eccentric annular passages by applying the finite volume method. The researchers focused on the effects of eccentricity, radius ratio and Rayleigh number on the Nusselt number and friction factor. The influence of buoyancy forces on heat transfer and friction was additionally demonstrated. Ingham and Patel [346] investigated the mixed convection of Non-Newtonian fluid in vertical eccentric annuli by developing a numerical technique with a combined finite difference method and finite difference scheme. The results revealed the effect of buoyancy on fluid velocity increase towards the hot outer wall. El-Shaarawi and Mokheimer [347] and El-Shaarawi et al. [348] adopted the fourth type of fundamental boundary conditions and performed a numerical study of laminar natural convection in vertical eccentric annuli under isothermal boundary condition. They showed the effect of eccentricity on Nusselt number and velocity profiles in an annulus with radius ratio of 0.5 and they also provided solutions for the fourth kind of thermal boundary condition for fully developed free convection in an eccentric vertical annular passage. Mokheimer and El-Shaarawi [349] conducted a numerical study of mixed convection in vertical eccentric annuli where they used a bipolar model and solved the model by linearized finite difference numerical method. The results obtained from the numerical solution revealed an increase in average Nusselt number with a decrease in eccentricity and increase in Gr/Re value. Mokheimer and El-Shaarawi [350] searched for numerical solutions for fully developed flow in an eccentric vertical annular duct with an open end with uniform heat sources and uniform heat flux from each wall. They obtained the solutions for the fourth type of fundamental boundary conditions. Mokheimer and El-Shaarawi [351] employed a coupled energy equation to numerically study laminar free convection in an open-ended vertical eccentric annular. The numerical results indicated the effect of radius ratio and eccentricity on Nusselt number. They obtained the physical value of the maximum possible limit for heat transfer and fluid flow in an annular channel. Jamal et al. [352] used a finite difference technique to numerically study natural convection in vertical eccentric annuli, whereby they demonstrated the effect of eccentricity on temperature distribution in a vertical annular. Nobari and Asgarian [353] presented a numerical study of mixed convection flow in a vertical eccentric annular using a bipolar cylindrical coordinate system and finite volume method dependent on Navier–Stockes equations along with energy equations for annulus. They found an increase in enhancement of heat transfer rate when internal fins were used and also good agreement with previous numerical studies. More recently, Nobari and Mehrabani [354] implemented a numerical study of heat transfer to fluid flow in an eccentric curved annular passage using the second finite difference method with a uniform staggered grid. They concentrated on the effect of Prandtl and Dean Numbers, eccentricity, and curvature ratio on the heat transfer and velocity distributions in an eccentric curved annular passage. They achieved greater enhancement of heat transfer in an eccentric curved annular passage than the eccentric straight one. Analytical and numerical studies of fully developed steady/unsteady natural convection flow with reactive viscous fluid through vertical annulus have been reported by Jha et al. [355]. They recognized that non-dimensional time increases with an increase in both temperature and velocity profiles up to a steady state value and they also obtained good agreement between numerical and analytical results.

4. Conclusions

Present review paper is concerned with experimental and numerical studies associated to forced, natural and mixed heat transfer to fluid flow in concentric and eccentric annular passage with different boundary conditions. The main conclusions of this review are considered below:

1. Nusselt number values for the boundary condition of uniform heat flux are higher than those at constant wall temperature.
2. Solutions for the effect of eccentricity on Nusselt number and velocity profiles in fully developed free convection annular passage with radius ratio of 0.5 for the fourth kind (Uniform heat flux at one wall, and the other wall maintains entering fluid temperature) of thermal boundary condition are possible to evaluate satisfactorily.
3. The rotation of the inner cylinder has the same effect on both Newtonian and Non-Newtonian fluid and the intensity of turbulence increases with rotation in Newtonian fluid but it decreases in Non-Newtonian fluid in a small gap.
4. The influence of roughness at wall on heat transfer coefficient by the turbulent thermal structures near the outer wall is more active than those near the inner wall due to the vortex regeneration processes between the inner and outer wall.
5. Increase of heater length, as well as the Darcy, Reynolds, Grashof and Rayleigh numbers enhances heat transfer in concentric and eccentric annular passages.
6. The increase of heat transfer rate to fluid flow in eccentric annular passage is higher in comparison to concentric annular passage due to effect of eccentricity on heat transfer and fluid motion.
7. The enhanced thermal conductivity and viscosity of nanofluids, and the random movement of nanoparticles causes further enhancement of heat transfer and stream functions.
8. The increase of velocity of rotation of inner or outer cylinder or both causes increase of improvement of heat transfer rate in annular channels.
9. The enhancement of heat transfer rate in eccentric elliptic and curved annular passage is larger than that of straight circular concentric annular passage.
10. Economic generation and transportation of energy by using nanofluid could provide a positive impact on energy crisis.

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